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AN EVALUATION OF THE POTENTIAL FOR
EXPERT SYSTEM APPLICATION TO MARINE
GAS TURBINE CONTROL

by

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Current shipboard gas turbine environments are in need of updating to reduce stressful, inadequate conditions on operators, and to provide improved casualty monitoring procedures for increased equipment longevity and reduced operating costs. These necessary improvements may be realized through a marine gas turbine health monitoring system capable of taking corrective control measures. Adequate technology exists today for such a system, as evidenced by two similar gas turbine diagnostic expert systems currently being tested by the Army and Air Force. Expert system tools such as CLIPS would significantly reduce the time, cost and integration difficulties in establishing a marine gas turbine expert system. This paper is an overview of published literature on Expert Systems and their current applications, with an evaluation of their potential for use in the marine gas turbine arena.

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I. <u>INTRODUCTION</u>: Today's shipboard gas turbine environment is in need of updating. Operators and watchstanders work under stressful and inadequate conditions. Effecitve catastrophic casualty control systems are nonexistent and day-to-day health monitoring procedures are in need of modernizing.

These necessary improvements may be realized through an expert system designed for marine gas turbine control. The control system would provide two primary diagnostic related functions. First, the system would provide catastrophic casualty monitoring, with the ability to take automatic corrective control measures. This function would be implemented and tested first prior to expanding the system's ability. The second diagnostic function to be developed would be the day-to-day health monitoring service. Faults whose symptoms increase or become worse over time would be identified so that human operators could prevent compounding machinery damage. Such a system would provide improved casualty monitoring procedures, thereby increasing equipment longevity and reducing operating costs.

In developing an expert system capable of the aformentioned functions the following steps need to be taken. First, a marine gas turbine health monitoring expert system program needs to be written. Such a program could be written using the "C" Lanugage Production System (CLIPS) and could be tested off-line using simulated data from a data file. The next step would be integrating the system to an actual gas turbine engine, such as the BOEING Model 502-6A gas turbine engine installed at the Naval Postgraduate School. After slight program modification to

account for actual or available input sensors the system could be tested by imposing casualties to the engine and comparing desired and actual responses.

II. EXPERT SYSTEM BACKGROUND: The specialized field of Expert Systems developed from the Artificial Intelligence (A.I.) branch of computer science. Specifically, that branch deals with expanding a machine's ability to perceive and reason, or accomplish tasks that appear to require intelligence. Expert systems are computer programs that solve complex, real-world problems which would require significant human expertise to interpret and solve. The solution of these involved problems is accomplished by the computer program's ability to simulate human reasoning, and arrive at similar conclusions or solutions as would "experts" in the field which the problem exists. The program's expert reasoning capability is largely accomplished through utilizing a vast body of knowledge pertaining to the area of interest, and ranging from general to highly specific information. Generally speaking, an Expert System consists of three parts:

1) a knowledge base consisting of facts and heuristics associated with the problem;
2) an inference or reasoning procedure for controlling knowledge information flow, by utilizing that information to draw conclusions;
3) a working memory or data base for data and problem status history (1).

The facts within the knowledge base are a commonly known, widely agreed upon collection of information, while the heuristics are commonly known rules-of-thumb held by the "experts", obtained through expertise in the field of interest. Generally speaking, the larger and more complex knowledge base expert systems are more capable of solving larger, more involved problems. Figure 1 represents a simplified Expert System structure.

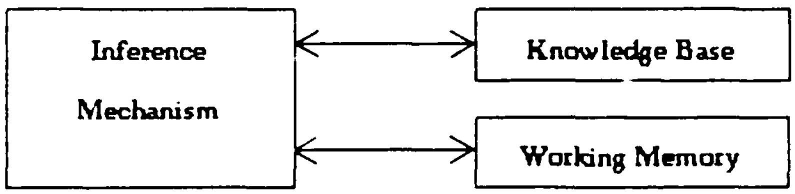

Figure 1. Major parts of an expert system. Arrows indicate information flow.

Three fundamental characteristics distinguish an expert system from conventional programs. First, while conventional programs make no distinction between knowledge and how knowledge is used, Expert Systems clearly separate the two. Secondly, expert systems utilize "inexact" reasoning or information that may not be one hundred percent true. Lastly, Expert Systems can be easily amended or their knowledge base increased through incremental modifications, while changes to conventional programs are often painstaking (2).

III. <u>EXPERT SYSTEM TYPES</u>: Although all expert systems consist of the three aforementioned core features, expert systems differ from one another in the choice of solution direction which is a

function of the inference mechanism. Expert system problem solving techniques fall under the following categories: Forward Chaining, Backward Chaining, Forward and Backward Processing Combined, and Event Driven (1). For the purposes of this paper only forward and backward chaining will be discussed because they are the two primary problem solving methods. Forward and backward processing utilizes a combination of forward and backward chaining to solve complex problems, and event driven processing is very similar to forward chaining.

Although expert systems' knowledge bases are composed of facts and heuristics provided by the field experts, in expert system programming language this information is known as "rules", and input or created data are termed "facts". In forward chaining the control strategy is initiated with a list of facts (or data) and utilizes rules (from the knowledge base) to arrive at a possible solution to the particular problem. Forward working systems are often characterized by being initiated with a small number of facts and are able to reach a large number of potential conclusions. A simple example of forward chaining, or data-directed inference, is in Table I.

Car won't start	Input data
If Car won't start, then battery dead	(Rule 1)
If battery dead, then need new battery	(Rule 2)
Need new battery	(Conclusion)

Table I. A Forward Chaining Expert System

Rather than starting with data, or a facts list, backward chaining commences with a particular goal or solution in mind, and works backwards. From existing rules it is determined what facts are necessary to obtain the particular stated goal. Existing facts are then checked to decide if the goal is correct. If facts are not available the user is asked to answer questions to generate facts and obtain a conclusion (3). An example using backward chaining or goal-directed reasoning is listed in Table II.

Need new battery	(Hypothesized Conclusion)
If need new battery, then the battery is dead	(Rule 1)
If the battery is dead, then the car won't turn over	(Rule 2)
If car won't turn over start, then need new battery	(Implied rule)
Will the car start?	(Data)

Table II. A Backward Chaining Expert System

Note that with the backward chaining strategy the action or right hand side (RHS) of the rule is examined and the former premise, when using forward chaining, is now the action section.

IV. <u>EXPERT SYSTEM APPLICATIONS</u>: Just as some problem solving techniques work better in certain situations, the same holds true with expert systems; in some applications expert system utilization is infeasible or impractical. The potential domain

of expert system utilization should meet the list of characteristics listed in Table III (2).

Genuine experts exist in the field,
Existing experts are much better than amateurs,
Skill must be routinely taught to amateurs/novices,
Experts must be capable of explaining corrective methods,
Task must be within reason (not too difficult),
Task should not require common sense,
Undertaking should have sufficient payoff to warrant construction.

Table III. Expert System Characteristic Domain

Although expert systems' development has only gained significant attention within the last decade, the first real expert system, and one meeting the characteristics of Table 1, - DENDRAL - was developed in the mid 1960's (4). Designed by Feigenbaum and Lederberg, DENDRAL is a forward chaining expert system used to determine the molecular structure of unknown chemical compounds using mass spectrometry data and, though over twenty years old, is still the most widely used expert system (5). Another historic expert system developed years ago is MYCIN. Authored by Shortliffe, MYCIN uses backward chaining from a hypothesized diagnoses of bacterial infections to gather support evidence for recommended antibiotic therapy (6). In addition to diagnosis and data analysis/interpretation functions expert systems exist which have design functions, such as SYN.

Written by Sussman, Steel and Dekleer, SYN assists in circuit design by determining values for electrical circuit components by utilizing forward reasoning and a knowledge base consisting of electrical laws and rules for creating and changing multiple views of circuit portions (1).

In the gas turbine arena there recently has been a number of expert system related developments. Currently underway is an endeavor to develop a general-purpose expert system inference engine to deal with determining the vulnerability of army combat vehicles and other systems to the wide range of threats presented in a hostile, modern warfare environment (7). The project is named "Genie", and the first application of the versatile, forward and backward chaining inference engine is an expert system, currently being developed, to assist human experts in determining the vulnerability of Army gas turbine jet engines (7). In order to improve the reliability and maintainability of gas turbine engines in the USAF inventory, the Air Force has been testing a new knowledge-based (expert system) diagnostic system which utilizes gas turbine vibration analysis data to diagnose rotordynamic faults (8). The diagnostic concept developed was successfully demonstrated on a test rig when the integrated system (knowledge-based system with implemented diagnostic logic and vibration data acquisition system) successfully diagnosed five input faults including: rotor unbalance, misalignment, rub, increased support flexibility and accessory vibrations (8). Lastly, the U.S. Army is developing an expert system which utilizes forward and backward reasoning to diagnose faults in a twin-engine gas turbine helicopter power train from instrument

panel data readings, thereby decreasing the evergrowing workload demands on the single cockpit pilot (9).

V. EXPERT SYSTEM MARINE GAS TURBINE APPLICATION: Just as the U.S. Army is concerned with relieving the cockpit burden of its helicopter pilots, attention needs to be focussed on easing the responsibilities of the watch-standers in the main population control spaces onboard Navy ships, primarily gas turbine propulsion vessels. The problems associated with the currently utilized real-time, sensor-based fault detection and diagnosis method of handling propulsion casualties has been well documented (10). Close examination of the real-time fault diagnosis process in just the reduction gear lube-oil subsystems revealed the following deficiencies: lube oil subsystem alarms often trigger simultaneously; watch-standers are responsible for compensating for an incomplete set of alarms and sensors; operators rely too heavily on technical manuals which do not correspond with real-time casualties; decision making, especially during critical maneuvering, is often difficult and stressful; diagnostic checks often create additional damage; and, lastly, even propulsion unit subsystems are vastly complex, compounding decision making difficulty (10). Simply put, Donald B. Malkoff, Capt./USN, states:

> Personnel are no longer able to fulfill the demands imposed upon them in their role as operators of gas turbine propulsion control units. Their greatest need is for assistance in the areas of fault diagnosis and the determination of proper corrective responses. These tasks can be adequately handled by the combined use of automation and computer expert systems (11).

Early (1974-1979) experience with the development of a shipboard gas turbine condition monitoring system (CMS) was not favorable, and reliability of monitoring hardware was required to improve by at least a factor of ten before it could be used as a reliable trouble shooting tool (12). However, in the last decade computer technology and controller-sensor reliability have substantially increased. Expert system tools such as NASA/Johnson Space Center's 'C' Language Production System (CLIPS) are currently available. CLIPS is a user friendly, forward chaining computer language designed for writing expert system applications. CLIPS was designed for portability, as it may be run on a range of microcomputers with little or no modifications. Additionally, CLIPS can easily be integrated at low cost to external systems, such as a marine gas turbine engine for health monitoring or diagnostic purposes.

An expert system designed to provide condition monitoring could, without significant difficulty, be expanded to take corrective casualty response actions, rather than providing operator recommendation only. The time delay between reading the recommendation and securing the engine could be quite costly in a real-time scenario, especially in view of catastrophic situations.

A health monitoring and controlling gas turbine expert system, besides being needed to relieve the current situation, meets the domain characteristics listed in Table III. Adequate time, however, would be required for the purpose of expanding the knowledge-base to the desired scope. Commonly known facts could, without much difficulty, be gathered from gas turbine technical

manuals and engineering casualty control procedures. Common faults could be listed with corresponding symptoms. For example, nozzle erosion in the power turbine would be indicated by a decrease in turbine inlet temperature, a decrease in shaft (output) horsepower and a drop in pressure ratio (assuming constant gas generator speed) (13). These facts could easily be turned into rules. The heuristics or secrets held by the field experts would take significantly longer to gather and then convert into meaningful rules. When writing the rules which will comprise the knowledge-base, attention must be placed on adjusting the rules to correspond with sensor data being input into the global data base. Adequate turbine analysis would require pressure and temperature measurements across the turbine, shaft vibration, and temperature and pressure measurements of the lubrication system (13).

VI. SUMMARY AND CONCLUSIONS: An expert system capable of marine gas turbine health monitoring and response is well within the scope of today's computer science technology. We base this conclusion on the existence of similar gas turbine diagnostic expert systems currently being tested by the U.S. Army and Air Force. Expert system tools such as CLIPS would significantly reduce the time, cost and integration difficulties in establishing a marine gas turbine expert system. The need for such a system is required in today's shipboard gas turbine propulsion environment. It would greatly reduce the burden on current operators, and potentially will significantly reduce operating costs due to proper corrective actions taken during equipment casualties. Such a

control system could provide a basis for increased ship combat effectiveness by providing quick response to potentially catastrophic situations.

REFERENCES

1) NBSIR 82-2505, "An Overview of Expert Systems," May 1982.

2) Dankell, D.D., "Expert System: Misconceptions and Reality," SAE Technical Paper Series 8603344, Feb. 24-28, 1986.

3) Moseley, W. and Zeagler, M.B., "Embedding Artificial Intelligence in Existing Applications," SAE Technical Paper Series 860336, Feb. 24-28, 1986.

4) Bramer, M.A., Research and Development in Expert Systems, Press Syndicated of University of Cambridge, London, 1985.

5) Weiss, S.M. and Kulikowski, C.A., A Practical Guide to Designing Expert Systems, Rowman & Allanheld Publishers, NJ, 1984.

6) Shortliffe, E.H. and Buchanan, B.G., Rule-Based Expert Systems, Addison-Wesley Publishing Company, MA, 1984.

7) Brundick, F., Dumer, J., Hanratty, T., and Tanenbaum P., "Genie an Inference Engine with Diverse Applications," Second Conference on Artificial Intelligence, Computer Society Press, 1985, pp. 473-480.

8) Aggarwal, B., Tecza, J. Giordano, J., and Brunner, R., "AI Gas Turbine Rotor Diagnostics," AD-A178996, Wright-Patterson AFB, OH, November 1986.

9) Simmons, D.W., Hamilton, T.P., Carlson, R.G., "HELIX: A Casual Model-Based Diagnostic Expert System," Journal of the American Helicopter Society, Vol. 32, Number 1, January 1987, pp. 19-25.

10) Malkoff, D.B., "Real-Time Fault Detection and Diagnosis: The Use of Learning Expert Systems To Handle the Timing of Events." AD-A174655, Navy Personnel R&D Center, San Diego, CA, December 1986.

11) Malkoff, D.B., "Innovations in the Control of Gas Turbine Propulsion Systems," Spring Meeting/STAR Symposium, Norfolk, VA, May 21-24, 1985.

12) Kandl, M.G., Groghan, D.A., "U.S. Navy, LM2500 Gas Turbine Condition Monitoring Development Experience," 80-G1-158 ASME, New York, NY, March 1980.

13) Meher-Homji, C.B. "A Feasibility Study of the Application of Artificial Intelligence Techniques for Turbomachinery Diagnostics," 8S-GT-102 ASME, New York, NY, March 1985.

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